AD NUMBER:	AD0831480

LIMITATION CHANGES

TO:

Approved for public release; distribution is unlimited.

FROM:

Distribution authorized to U.S. Gov't. agencies and their contractors; Export Control; 1 DEC 1967. Other requests shall be referred to Air Force Cambridge Research Laboratories, Office of Aerospace Research (CRDM), Hanscom AFB, Bedford, MA 01730

AUTHORITY

22 Dec 1971 per AFCRL ltr

AD831480

AFCRL-68-0155

ROCKET ANTENNA MULTIPACTOR BREAKDOWN UNDER DYNAMIC PRESSURE CONDITIONS

By

G. AUGUST J. E. NANEVICZ J. B. CHOWN

CONTRACT AF 19(628)-4800
PROJECT NO. 4600
TASK NO. 460010
WORK UNIT NO. 46001001

Scientific Report 6

December 1967

Contract Monitor: CHARLES E. ELLIS
MICROWAVE PHYSICS LABORATORY

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS 01730

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Stanford Research Institute 333 Ravenswood Avenue Menlo Park, California 94025	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP n/a

3. REPORT TITLE

ROCKET ANTENNA MULTIPACTOR BREAKDOWN UNDER DYNAMIC PRESSURE CONDITIONS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific. Interim.

5. AUTHOR(S) (First name, middle initial, last name)

Gerald August John B. Chown
Joseph E. Nanevicz

6. REPORT DATE December 1967	7a. TOTAL NO. OF PAGES 43	7b. NO. OF REFS 6
8a. CONTRACT OR GRANT NO. AF 19(628)-4800 b. PROJECT NO. Task, Work Unit Nos. 4600-10-01 c. DoD Element 62405304 d. DoD Subelement 674600	9a. ORIGINATOR'S REPORT NUMBER(S) Scientific Report 6, SRI Project 5359 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFCRL-68-0155	

10. DISTRIBUTION STATEMENT

2 - This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of AFCRL (CRDM), L.G. Hanscom Field, Bedford, Massachusetts 01730

11. SUPPLEMENTARY NOTES TECH, OTHER	12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories (CRD) L. G. Hanscom Field Bedford, Massachusetts 01730

13. ABSTRACT

An anomalous high-altitude voltage breakdown on a VHF antenna aboard Nike-Cajun Rocket AD 6.841 is investigated. A previously proposed cause of the anomaly, a dynamic pressure variation interacting with a multipactor discharge, is experimentally investigated.

The multipactor discharge under dynamic pressure conditions results in a unique form of voltage breakdown hitherto undescribed. This discharge form is called a gas-augmented-multipactor (GAM) discharge. The GAM discharge may persist for several minutes. Certain aspects of the GAM discharge more closely resemble the usual gas discharge breakdown than they do the usual multipactor discharge. The GAM discharge has an effect upon antennas comparable to that of the usual gas discharge breakdown at certain pressures in the latter's operating regime.

The flight-test record is examined and compared with the laboratory data. It is concluded that the anomalous breakdown was due to a GAM discharge.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Antennas						
Voltage breakdown						
High-altitude tests						
Multipactor breakdown						
Fast-pumpdown test						

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

AFCRL-68-0155

ROCKET ANTENNA MULTIPACTOR BREAKDOWN UNDER DYNAMIC PRESSURE CONDITIONS

By

G. AUGUST J. E. NANEVICZ J. B. CHOWN

SRI Project 5359

CONTRACT AF 19(628)-4800
PROJECT NO. 4600
TASK NO. 460010
WORK UNIT NO. 46001001

Scientific Report 6

December 1967

Contract Monitor: CHARLES E. ELLIS
MICROWAVE PHYSICS LABORATORY

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of AFCRL (CRDM), L. G. Hanscom Field, Bedford, Massachusetts 01730.

Approved: T. MORITA, MANAGER
ELECTROMAGNETIC SCIENCES LABORATORY

D. R. SCHEUCH, EXECUTIVE DIRECTOR
ELECTRONICS AND RADIO SCIENCES

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS 01730

Copy No. 156

ABSTRACT

An anomalous high-altitude voltage breakdown on a VHF antenna aboard Nike-Cajun Rocket AD 6.841 is investigated. A previously proposed cause of the anomaly, a dynamic pressure variation interacting with a multipactor discharge, is experimentally investigated.

The multipactor discharge under dynamic pressure conditions results in a unique form of voltage breakdown hitherto undescribed. This discharge form is called a gas-augmented-multipactor (GAM) discharge. The GAM discharge may persist for several minutes. Certain aspects of the GAM discharge more closely resemble the usual gas discharge breakdown than they do the usual multipactor discharge. The GAM discharge has an effect upon antennas comparable to that of the usual gas discharge breakdown at certain pressures in the latter's operating regime.

The flight-test record is examined and compared with the laboratory data. It is concluded that the anomalous breakdown was due to a GAM discharge.

CONTENTS

FOREWORD

This report was prepared by Stanford Research Institute (SRI), Menlo Park, California, and is the sixth in a series of Scientific Reports issued under Air Force Contract AF 19(628)-4800, Project No. 4600, Task No. 460010. The work was administered under the Office of Aerospace Research of the Air Force Cambridge Research Laboratories. Mr. Charles Ellis was the Air Force task engineer.

The report presents the results of a study of a particular topic in the general area of problems associated with the radiation and reception of electromagnetic energy from aircraft and guided missiles. The principal investigator, Dr. J. E. Nanevicz, was responsible for research activity under Stanford Research Institute Project 5359.

With the publication of this report, the Scientific Reports issued in this series to date are as follows:

Scientific Report 1

"An Experimental Study of Non-Linear Plasma Wave Interaction," by W. C. Taylor, AFCRL-65-654 (August 1965).

Scientific Report 2

"Rocket Motor Charging Experiments," by E. F. Vance and J. E. Nanevicz, AFCRL-66-497 (June 1966).

Scientific Report 3

"SRI Participation in Voltage Breakdown and Rocket Charging Experiments on AFCRL Nike-Cajun Rocket AD 6.841," by J. E. Nanevicz, J. B. Chown, E. F. Vance, and J. A. Martin AFCRL-66-588 (August 1966).

Scientific Report 4

"Measurement of RF Ionization Rates in High-Temperature Air," by W. C. Taylor, J. B. Chown, and T. Morita AFCRL-67-028 (March 1967).

Scientific Report 5

"Multipactor Discharge Experiments," by E. F. Vance and J. E. Nanevicz AFCRL-68-0083 (December 1967).

Scientific Report 6

"Rocket Antenna Multipactor Breakdown Under Dynamic Pressure Conditions," by G. August, J. E. Nanevicz, and J. B. Chown (December 1967).

ILLUSTRATIONS

TABLES

I INTRODUCTION

On Air Force Cambridge Nike-Cajun flight AD 6.841 of 20 April 1965, anomalous voltage breakdown of a VHF antenna was observed. The anomalous breakdown was the experiencing of gas discharge effects--i.e., impedance variation and signal attenuation--at altitudes where only a multipactor discharge was expected. Stanford Research Institute had participated in the test program, and had made voltage breakdown tests on an antenna similar to the flight antenna. The SRI participation and test results are described in an earlier report, AFCRL-66-588.[1*] The SRI laboratory tests had not revealed any anomalous behavior during multipactor breakdown.

Voltage breakdown limits the power than can be radiated from rocket-borne antennas. Gas-discharge breakdown is always a severe problem, but it occurs only at low altitudes. A multipactor breakdown can occur at high altitudes, but it is not usually a significant problem. It is important, therefore, to understand the anomalous breakdown.

In AFCRL-66-588, various explanations were suggested for the anomalous behavior. These explanations all assumed that sufficient gas was released during the multipactor discharge to cause a transition into a gaseous discharge. One possible source of gas was outgassing from the rocket, and from the antenna surfaces in particular. This outgassing was due to adjustment toward equilibrium, of the adsorbed surface gases under the dynamic pressure conditions of flight. Such outgassing was absent in the laboratory tests, where test pressures were attained after several hours of pumping, rather than in the few minutes of the flight test.

Another possible source of gas was due to multipactor cleanup of adsorbed surface gases. The usual laboratory tests, made after attaining steady-state conditions, ignored such transient behavior.

---

*References are given at the end of the report.

A third possible gas source was liberation and/or decomposition of surface contaminants by the multipactor discharge. Suggested contaminants were salt particles, due to salt spray from the ocean (launch site was at Wallops Island, Va.), and oil films rubbed onto the antenna from handling by launch technicians. It is known that oils promote and intensify multipactor discharges.[2,3]

In an effort to explain the anomalous behavior, some experiments to test the above suggestions were devised and carried out at Stanford Research Institute. The experiments investigated multipacting under a dynamic pressure variation simulating the flight-test ambient-pressure variation. The same model antenna as the flight-test antenna was used, along with similar operating conditions. Both clean antennas, and antennas with oil, salt, or oil and salt contaminants were tested.

The experiments were cosponsored by Lincoln Laboratory and Air Force Cambridge Research Laboratory. Some experimental results have been previously reported to Lincoln Laboratory.[2] The present report contains additional experimental results, together with appropriate flight-test data, and conclusions about the anomalous breakdown.

Results of measurements of electron density as a function of time in a multipactor discharge at constant pressure are also reported here. These measurements were made for Lincoln Laboratory.[2] However, they clarify the behavior of the multipactor discharge in the presence of cleanup of adsorbed surface gases.

II TEST FACILITIES AND EQUIPMENT

A. Fast-Pumpdown Facility

The dynamic pressure variation of the flight test was simulated in a fast-pumpdown facility. Multipactor breakdown and gas-discharge breakdown were investigated while the pressure was rapidly varied. Tests were made with both clean and contaminated quadraloop antennas.

Figure 1 is a block diagram of the fast-pumpdown facility. The

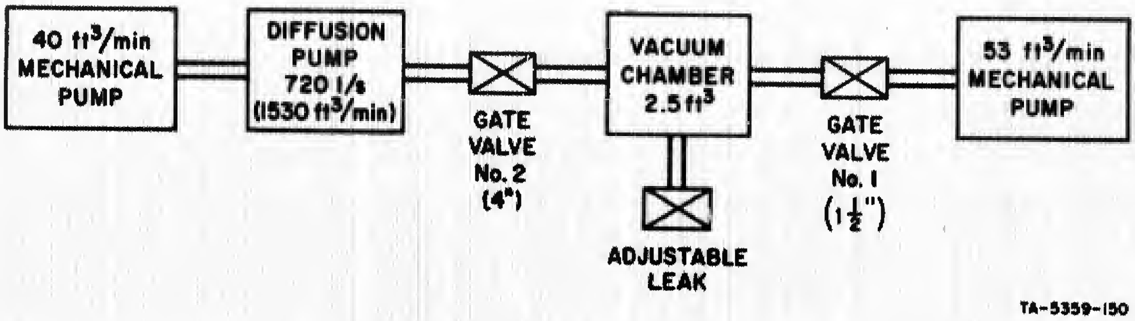

FIG. 1 BLOCK DIAGRAM OF FAST-PUMPDOWN SYSTEM

vacuum chamber is a small cylindrical bell jar, 24 inches high and 15 inches in diameter. Prior to a test, both sets of pumps were operating, the diffusion pump was at operating temperature, the gate valves were closed, and the chamber was at atmospheric pressure. At time zero, Gate Valve 1 was opened, and evacuation began. Gate Valve 2 was opened at some pressure below 350 μ, and the diffusion pump completed the evacuation to below 1 μ. Gate Valve 1 was closed shortly after opening of Gate Valve 2, so that the diffusion pump did not work against the back pressure of the 53-cfm mechanical pump ($\sim$ 20 μ). An adjustable gas leak was used to control the speed of evacuation.

Figure 2 shows the fastest pressure variation attainable in the' facility, plotted as an equivalent altitude versus time. This variation was obtained with no adjustable leak used; the 53-cfm pump operated

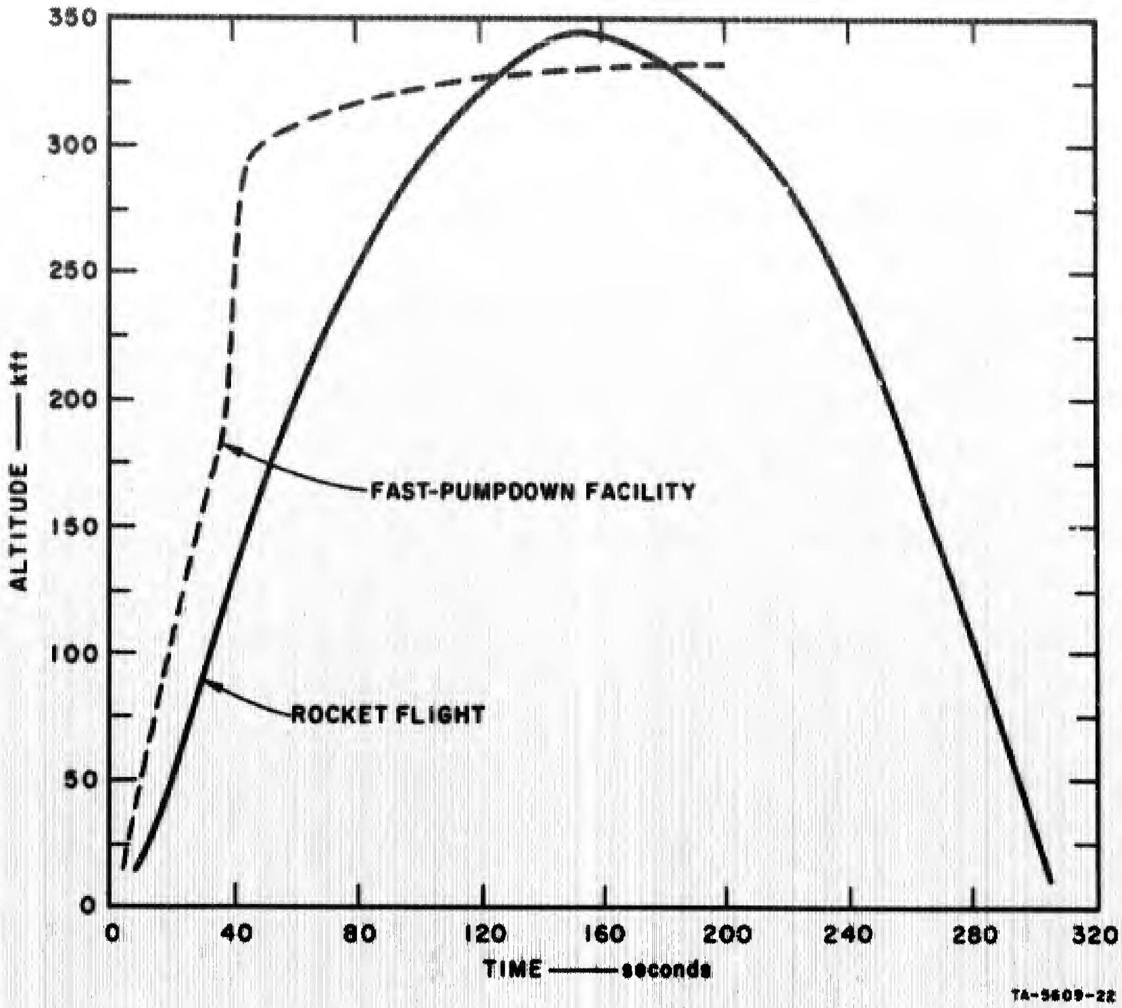

FIG. 2 ALTITUDE-vs.-TIME PROFILE OBTAINED IN FAST-PUMPDOWN FACILITY, COMPARED WITH ROCKET-FLIGHT PROFILE

from 0 to 50 seconds, and the diffusion pump operated after 36 seconds. For comparison, the altitude-vs.-time profile of Nike-Cajun flight AD 6.841 is also shown. As can be seen, the rapid pressure variation of the rocket flight was successfully simulate , except at altitudes above 325 kft, where outgassing from bell-jar walls slowed the evacuation.

The descent phase of a rocket flight was simulated in the fast-pumpdown chamber by first closing both gate valves when at high vacuum, and then admitting air into the chamber through the adjustable leak.

In operation, the leak was adjusted so that a pressure of 1 μ, corresponding to 300 kft, was reached in about 60 seconds. Pumping was

normally continued for one minute after this time, and then the simulated descent phase was started. Typical overall test times were 3 to 5 minutes.

B. <u>VHF Quadraloop Antenna</u>

A quadraloop antenna, the same model as the one flown on the Nike-Cajun flight, was used for the fast-pumpdown tests. Figure 3 shows a

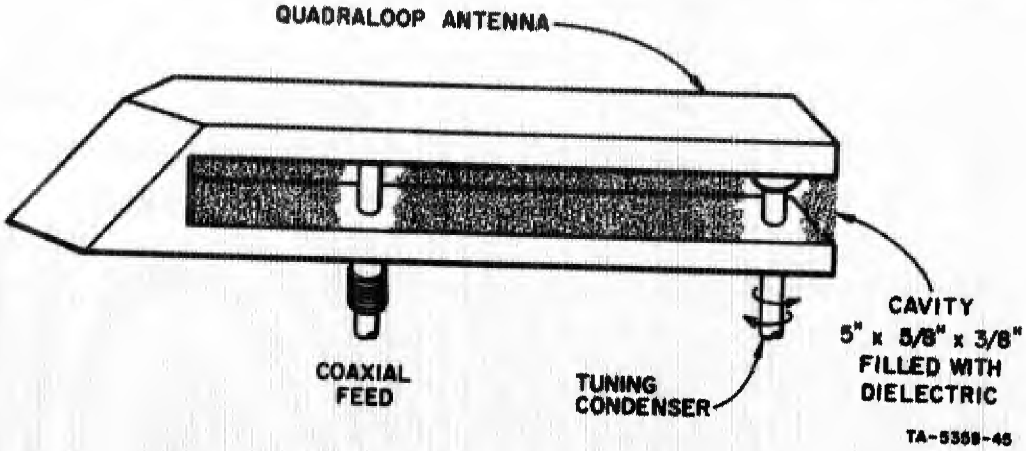

FIG. 3 QUADRALOOP ANTENNA

schematic diagram of this antenna. Figure 4 shows the antenna mounted on a cylinder (simulating the Nike-Cajun body), in the fast pumpdown facility. The antenna was operated at 259.9 MHz, and had a VSWR of less than 1.5. The flight-test antenna was operated at 259.7 MHz, and had a VSWR of 4.3 during most of the rocket ascent. However, the VSWR changed abruptly to 2.0 during the flight, and later reverted back to approximately the original VSWR. The cause of these abrupt changes in VSWR is unknown.

Both the flight-test antenna and the laboratory antenna were operated with peak incident powers of 25 W, amplitude-modulated at 1 Hz. The flight-test antenna modulation was trapezoidal, whereas the laboratory antenna modulation was half-sinusoidal.

C. <u>Chamber Environment</u>

The bell jar contained an auxiliary multipactor discharge. This provided an ambient plasma, which simulated the ionospheric plasma encountered during the Nike-Cajun flight. The discharge occurred between

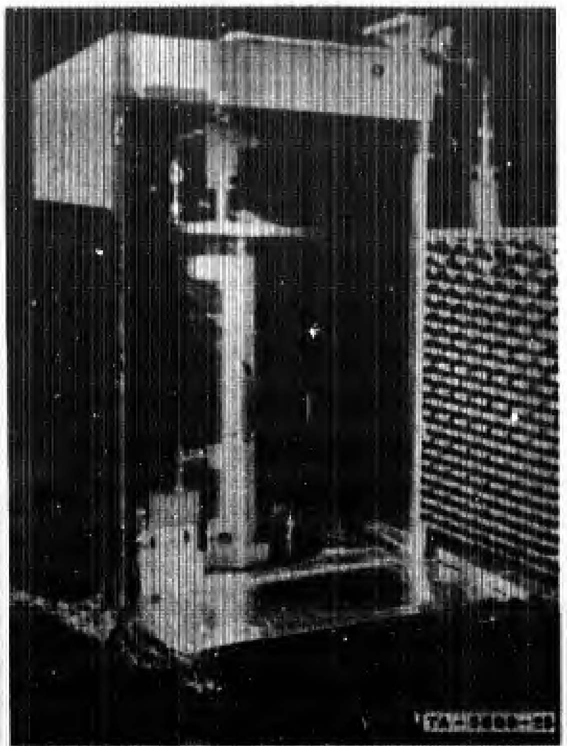

FIG. 4 FAST-PUMPDOWN FACILITY

two parallel 4-inch-diameter circular aluminum plates separated by 1/2 inch. An RF field was provided by a 10-W, 100-MHz transmitter. The discharge produced a plasma with density $\sim 10^4$ electrons/cc, and electron temperatures ~ 4 eV.

A polonium strip was placed inside the bell jar to provide reliable starting of multipactor and gas discharges in the event the auxiliary multipacting discharge was not operating.

Microwave absorber was placed outside the glass bell jar to eliminate exterior reflections, and to shield other test equipment.

D. Photomultiplier Detector

A multipactor discharge is most easily detected by monitoring its visible light output. A photomultiplier tube was placed outside the bell jar, pointed at the quadraloop antenna. Its sensitivity was adjusted so that it produced basically no output when the multipactor discharge was so faint as to be barely visible. The photomultiplier

was shielded from the light output of the auxiliary multipactor by appropriate positioning, pointing, and collimation. Switching of the ambient plasma source on and off, at pressures below 10 μ, did not disturb the photomultiplier output.

In the presence of a gas-discharge breakdown, the photomultiplier output was always saturated. This happened even at the lowest pressures of the gas-discharge regime, where the discharge was quite diffuse and of low luminosity. The higher light output of the gas discharge, as compared to the multipactor discharge, is probably due to its higher ion density, and subsequent photoemission upon recombination.

The fast-pumpdown chamber was darkened to permit photomultiplier operation in the lighted laboratory. The laboratory was sometimes darkened to permit visual observation and photographic recording of the voltage breakdown.

E. Other Equipment

Pressure, from 760 torr to 1 μ, was recorded on a strip-chart recorder using a Magnevac gauge (Pirani-type). Pressure below 1 μ was recorded manually, using a reference Phillips ionization gauge.

Both incident and reflected RF power, to and from the quadraloop antenna, were monitored using dual directional couplers. One coupler fed two slow-speed (1-Hz response) power meters, used for calibration, while another coupler fed two crystal detectors whose outputs were amplified and then recorded. Variations slower than 100 Hz could be followed with this arrangement.

A light-beam oscillographic recorder (Visicorder) was used with the following inputs: incident power; reflected power; pressure (from Magnevac); photomultiplier output; time base; and event marker (for various valve operations, ambient plasma operation, or Phillips gauge manual readings).

F. Contaminant Tests

The role of contaminants as a possible explanation for the anomalous breakdown was examined by repeating the fast-pumpdown tests using antennas having surface contaminants.

Surface contaminants usually lower the power required to initiate and extinguish multipacting. Oil films, oxide films, various salts, and most dielectric substances all have a secondary emission coefficient of unity at a lower electron energy than do most clean metal surfaces.[3,4]

The quadraloop antenna and the cylinder surface immediately about it were cleaned by wiping with alcohol to remove any oils and grease, rinsing with water, and air drying. When contaminants were used, the surface was first cleaned and then the contaminants applied. Hand oils and hand salts were obtained by repeated handling of the antenna area. Fine salt granules were deposited on the antenna by spraying from an atomizer containing a saline solution, and letting the excess water evaporate.

III TEST RESULTS--MULTIPACTING UNDER DYNAMIC CONDITIONS

A. Introduction

The laboratory tests found that the initial or transient phase of the multipactor discharge was quite different from the long-term multipactor discharge. This initial phase shall henceforth be called a gas-augmented-multipactor discharge, or GAM discharge, while the useage "multipactor discharge" shall be reserved for the long-term multipactor discharge, which is the one normally observed in the laboratory.

The GAM discharge is considered to be a dynamic gas-pressure variation interacting with what would otherwise be the multipactor discharge. The dynamic pressure variation results from: ambient pressure changes; multipactor cleanup of surface gases; outgassing from electrodes and surrounding surfaces; and liberation and/or decomposition of surface contaminants.

B. Fast-Pumpdown Tests

1. General Discussion

Prior to a test, the antenna had been under vacuum for variable periods of time. It was then left sitting at atmospheric pressure for periods ranging from ten minutes to several days. The fast-pumpdown test was started, and gas-discharge breakdown began at about 30 torr and continued down to about 30 μ. The plasma source was turned on at 10 μ (265 kft), and the GAM discharge began almost immediately. For the range of powers used here, no GAM discharge initiated in the absence of an ambient plasma. Usually, shutting off the ambient plasma also extinguished a GAM or multipactor discharge.

In some cases, RF power was not applied until the pressure had dropped below 1 μ (300 kft). In those cases, no gas discharge occurred to modify the surface contitions.

The tests were not repeated enough to establish any differences ascribable to length of time left standing at atmospheric pressure, or presence of an intervening gas discharge.

The GAM discharge produced changes in incident power, reflected power, and discharge light output. These changes were different from those produced by gas-discharge breakdown or multipactor discharge. All changes were measured from the pre-breakdown value of those quantities.

2. Modulation Cycle Shapes

Figure 5 shows the modulation cycle shapes for incident power,

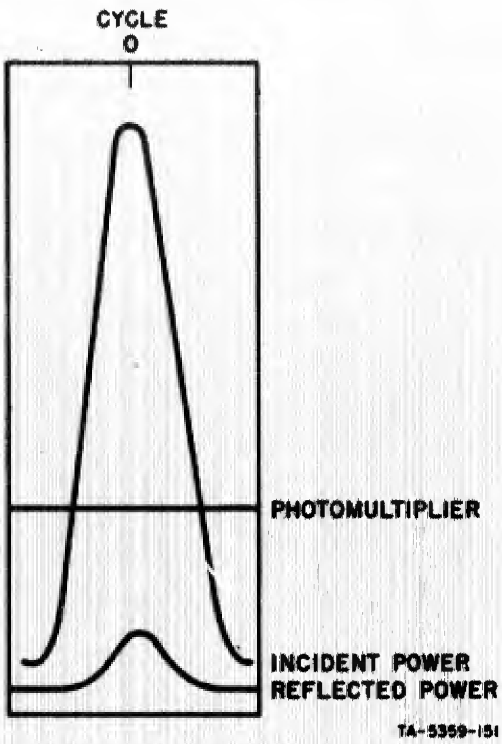

FIG. 5 PRE-BREAKDOWN MODULATION CYCLE

reflected power, and light output, prior to breakdown. In this case, the peak incident power was about 25 W, and the peak reflected power was about 1.3 W. There was no light output. The power scales are almost linear. The antenna incident power, reflected power, and VSWR, measured prior to any breakdown, and at the peak of a modulation cycle, are called the nominal values of those parameters.

Figure 6 shows the modulation-cycle shapes characteristic of the last cycle of gas-discharge breakdown, at about 30 μ. Note that the photomultiplier output is saturated.

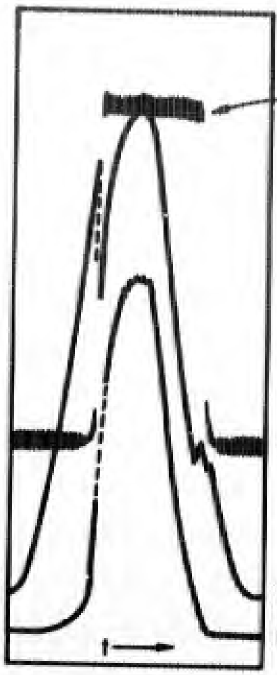

FIG. 6 LAST CYCLE OF GAS-DISCHARGE BREAKDOWN

Figure 7 shows some modulation-cycle shapes of the GAM discharge. In this case, the antenna had been pumped to below 1 μ before applying RF power. The modulation cycles are numbered in cycles, or seconds, from the start of the GAM discharge.

Cycle 5 shows a typical "quasi-gas-discharge phase" which is characterized by a VSWR higher than the nominal (predischarge) value and by a saturated photomultiplier output similar to that seen in gas discharge breakdown. The peak incident power was 15 W and the peak reflected power was about 2.9 W.

Cycle 10 represents a typical gas-enchanced multipactor discharge, characterized by small effects on incident power, reflected power, and VSWR and by unsaturated light output. The multipactor discharge improved the antenna match, and so resulted in lower reflected power and VSWR than the nominal values. The multipactor discharge need not necessarily improve the antenna match--whether or not it does so depends on the antenna configuration and tuning.

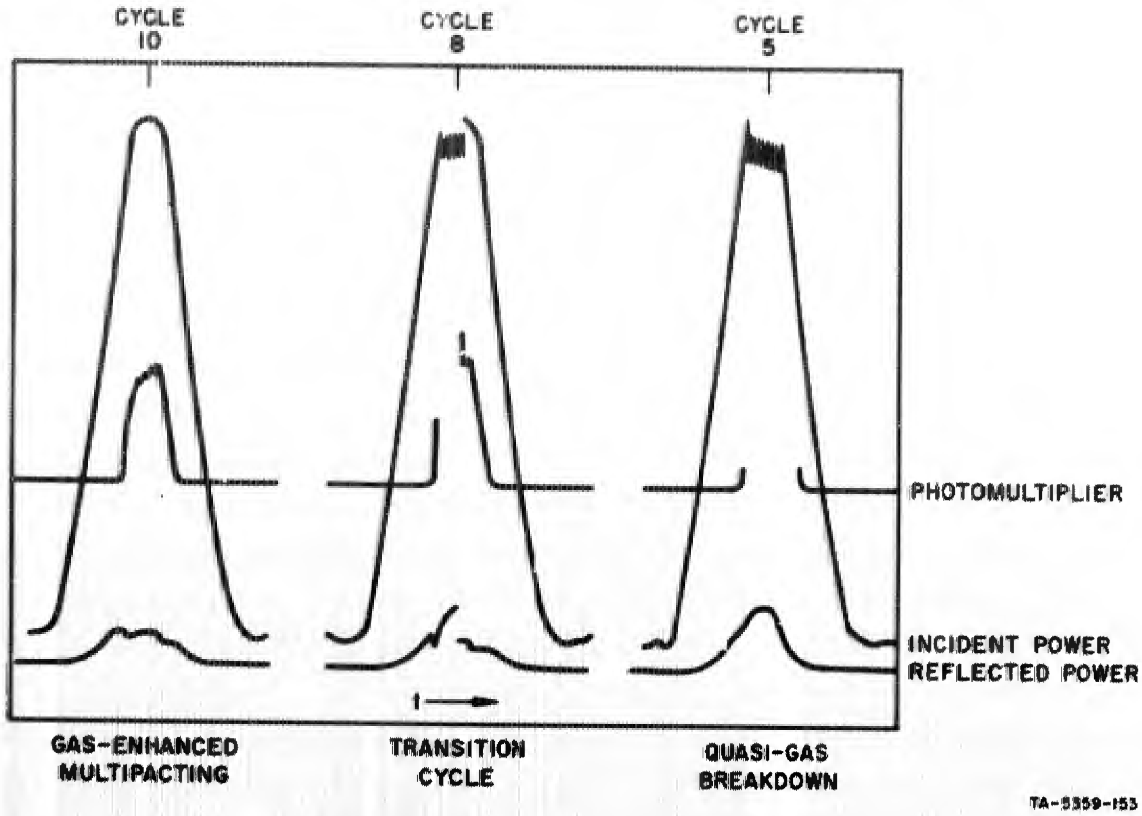

FIG. 7 MODULATION CYCLES DURING GAS-AUGMENTED-MULTIPACTOR BREAKDOWN

On Cycle 10, with a well-matched antenna, onset of the multipactor discharge produced a distinct notch in the incident and reflected powers. On successive cycles, the notches become less well defined, and eventually cannot be distinguished. Simultaneously the light output during multipacting gradually diminishes, and eventually cannot be distinguished from the slight light output during multipactor discharge. Thus, Cycle 10 gradually reverts to the shape shown in Fig. 5 for pre-breakdown or nominal conditions.

Cycle 8 shows a transition cycle, characterized by partial quasi-gas-discharge qualities, and by partial gas-enhanced-multipacting qualities. Here breakdown began as a quasi-gas discharge, and then charged to a gas-enhanced multipacior discharge. This order is sometimes reversed, and occasionally several such transitions occur within the same cycle.

3. Antenna VSWR

At initial gas breakdown near 30 torr, the VSWR jumps abruptly from its nominal value, and steadily increases as the pressure decreases, until final gas breakdown is reached near 30 μ. Between 30 μ and the onset of the GAM discharge, the VSWR reverts to its nominal value. At the onset of the GAM discharge, the VSWR again increases abruptly, but usually to a value below that for gas breakdown at 30 torr, and well below the value for gas breakdown at 30 μ. Thereafter, except perhaps for 4 or 5 seconds immediately following, the VSWR steadily decreases through the remainder of the GAM quasi-gas-discharge phase. In the gas-enhanced-multipactor phase, the VSWR generally begins at a low value, and then steadily increases and approaches the nominal value. In this phase, and in the usual classical multipactor discharge, the discharge often improves the antenna match.

The classical multipactor discharge, and/or gas-enhanced-multipactor phase of a GAM discharge, may not always improve the match of an arbitrary antenna. The multipactor-produced plasma is inductive and will detune an antenna turned to resonance, thereby worsening the match. However, in the classical multipactor discharge, the electron density is well below critical density, so that this inductive effect will be small for the quadraloop antenna. The effect will be a function of antenna Q. The multipactor-produced plasma also absorbs energy from the RF field, and that generally improves the antenna match.

Since the multipactor discharges under consideration can either increase or decrease the VSWR, the VSWR is clearly a poor indicator of a GAM discharge. However, the quantitative effects of the quasi-gas discharge phase upon the reflected power and VSWR of the quadraloop antenna are still important. Table I lists some VSWR data for various surface conditions, taken under the normal experimental conditions, and VSWR observed when the quadraloop antenna was pumped to below 1 μ before applying RF power so that no gas discharge occurred prior to the multipacting breakdown.

Table I

ANTENNA VSWR WITH AND WITHOUT GAS DISCHARGE
FOR THE VARIOUS SURFACE CONDITIONS

	VSWR With Gas Discharge			VSWR Without Gas Discharge		
	Clean Surface	Oiled Surface	Oiled and Salted Surface	Salted Surface	Clean Surface	Oiled and Salted Surface
Nominal Value	1.20	1.34	1.21	1.05	1.80	1.72
Value at first gas breakdown, about 30 torr	2.56	2.60	3.82	2.98		
Value at last gas breakdown, about 30 μ	21	10.2	9.63	9.52		
Value at first complete quasi-gas discharge cycle	1.81	2.36	3.48	1.96	1.97	2.56
Value at last "multipactor discharge" cycle	1.38	1.64	1.91	1.22	1.57	1.62

The data in Table I are representative of maximum effects expected during the GAM discharge. Sufficient test data was not collected to warrant averaging. The nominal VSWR of the quadraloop antenna, at the fixed operating frequency, gradually increased during the test series (1.2:1 to 1.8:1). This may have been due to internal heating and resulting mechanical strains gradually changing the antenna tuning. The VSWR during the quasi-gas-discharge phase stayed approximately constant, however, and the maximum reflected power stayed in the 2-to-4-W range, for about 20 to 25 W incident power.

Generally, the VSWR during multipactor discharge improved over the nominal value. However, in some cases with exceptionally good nominal matches, the VSWR during multipactor discharge was slightly worse than the nominal values.

The VSWR data led to the following conclusions. First, for an antenna not initially well matched, the VSWR during quasi-gas breakdown may differ so little from the nominal value as to not be readily detectable. Second, on clean antennas, the GAM discharge quasi-gas phase does not result in substantial antenna mismatch--the peak effects are comparable to that of the first gas-breakdown cycle at about 30 torr. Third, contaminants increased the mismatch, during multipacting, over clean antenna values, with oil and salt in combination giving the greatest effect, salt alone the least effect, and oil alone giving an intermediate effect.

It is not safe to extrapolate the first and second conclusions above to antennas of different geometry.

4. Light Emission

The photomultiplier output, indicating light emission, is a more reliable indicator of multipacting than is a VSWR measurement. Figure 8 shows the photomultiplier output for two cases involving similar

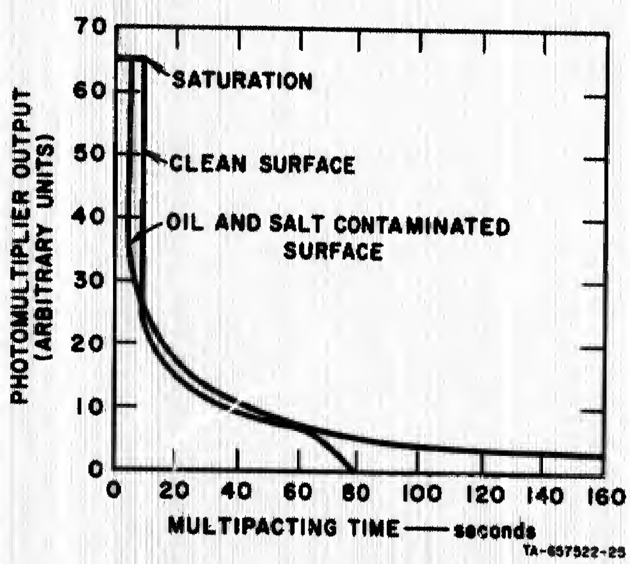

FIG. 8 LIGHT EMISSION DURING MULTIPACTING

pressure-pumping time conditions. During the first 5 to 10 seconds, the GAM discharge results in saturated light output, indicating conditions resembling a gas discharge, with many excited gas atoms or ions available to furnish photons. The light output gradually diminishes over a minute or longer, depending on the surface conditions. Both oil, and oil plus salt contaminants gave the greatest changes from clean surface multipacting, while salt contaminants alone were intermediate in behavior.

The duration of the GAM discharge can be measured either by its effect on the incident and reflected power, or by its light emission. The latter is a more sensitive indicator since, as indicated earlier, the gas-augmented multipactor discharge goes smoothly into the multipactor discharge with only a slight change in VSWR. Table II illustrates the duration of the GAM discharge and its quasi-gas-discharge phase.

Table II

DURATION OF GAM DISCHARGE PHASES

Condition	Quasi-Gas Discharge		GAM Discharge	
	Range (sec)	Average (sec)	Range (sec)	Average (sec)
Clean	7 - 21	12	25 - 84	63
Salt	13 - 24	18	28 - 88	58
Oil	77	77	32 - 91	64
Oil & Salt	6 - 50	25	65 -313	155

C. Electron-Density Measurement

The transient variation of the multipactor discharge, due to multipactor cleanup of adsorbed surface gases or contaminants, has been investigated by measuring the electron-density variation with time, for a multipactor discharge.[2] The multipactor discharge, in this case, occurred between the conductors of a strip transmission line. The strip transmission line is part of a back-to-back coaxial-stripline balun. The strip transmission line was 8 inches long and 1.5 inches

wide, with an adjustable spacing between the conductors. A Faraday cage located in one wall of the strip line was used to monitor the electron density in the multipacting discharge. The RF power for these experiments was furnished by a 2-kW CW source operating at 800 MHz.

The electron-density measurements are good indicators of the severe effects of the GAM discharge. Although these measurements were made for a transmission line, rather than an antenna, and for different frequency, they strikingly illustrate the initial cleanup process. Figures 9 and 10 show the measured electron density and electron current for two cases. Figure 9 shows the electron density, for an initial application of RF power to the strip transmission line, after pumpdown. The power was sufficient to initiate multipacting without an ambient plasma. The pressure was 2×10^{-5} torr (390 kft). The applied RF voltage was about 25 percent larger than that required to initiate multipacting. The critical electron density, where the plasma frequency is equal to the operating frequency, is about 8×10^{9} electrons/cc here. Thus, electron densities in excess of 5 percent of critical density are obtained for 55 seconds. The first peak, near zero time, is believed to be desorption of the monolayer of gas atoms at the surface, due to electron bombardment. The second electron peak is believed due to heating. It can be calculated, with some assumptions, that the temperature rise of the strip transmission line should be about 80°C after 55 seconds. This relatively abrupt rise in temperature probably causes outgassing of some gas absorbed in the interior of the metal. Dushman has indicated that metals can absorb about their own volume of gas at STP, and that it may take many hours to release this by slow diffusion through the metal under vacuum, unless the metal is heated.[5]

Figure 10 shows the electron density after several trials. This was the fifth test; the stripline had been under vacuum 7-1/2 hours, and 4 hours had elapsed since the previous test. The same pressure and power levels were used in all five tests. The same initial peak occurs, and a second peak occurs about 140 seconds later. The magnitudes of these two peaks are about 1/2 the value shown in Fig. 9. Again, sub-

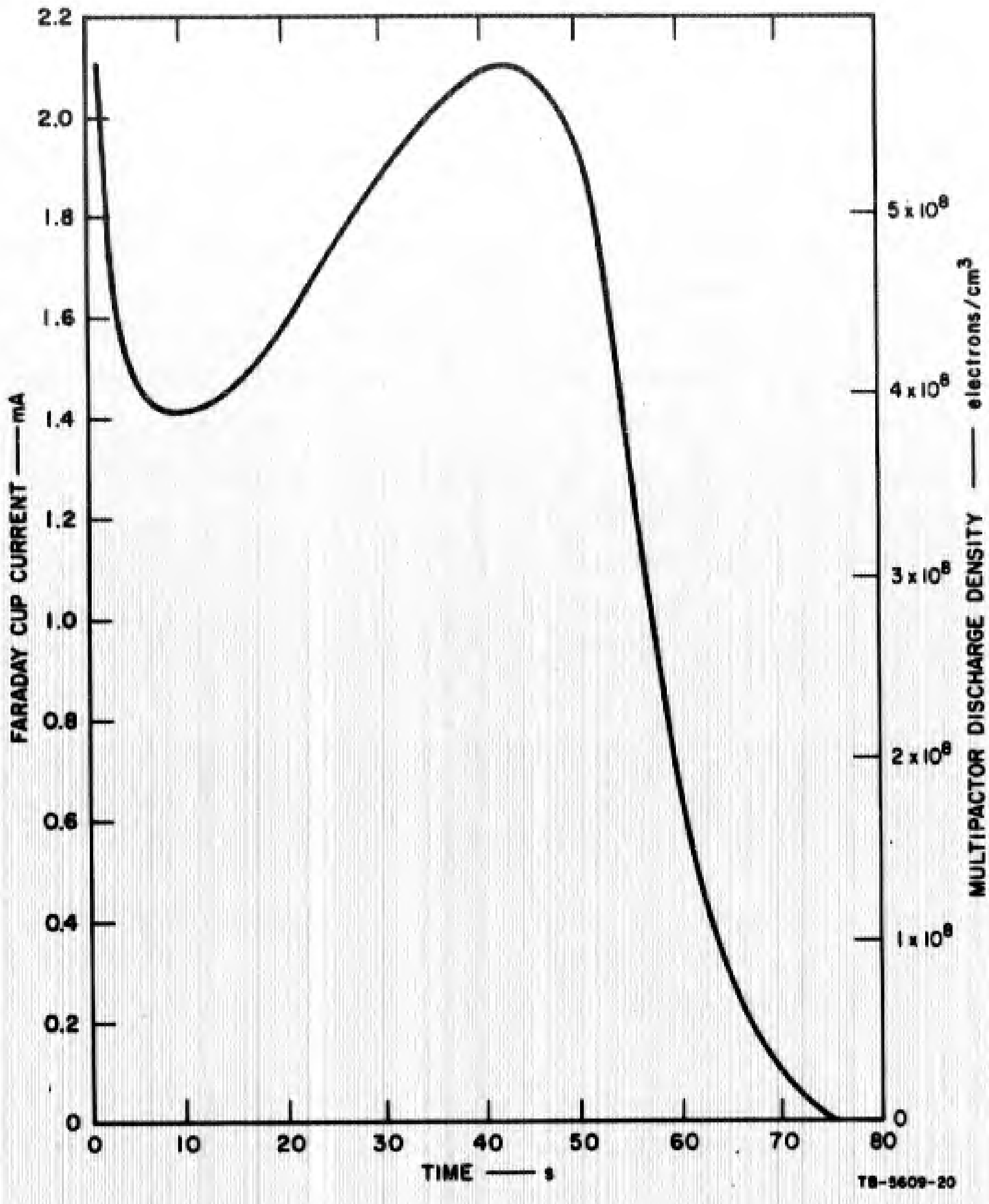

FIG. 9 MULTIPACTOR ELECTRON DENSITY VS. TIME, CASE 1. Strip-line balun, 3/16" spacing, 1800 W power, 2 × 10^{-5} torr, under vacuum 2-½ hrs.

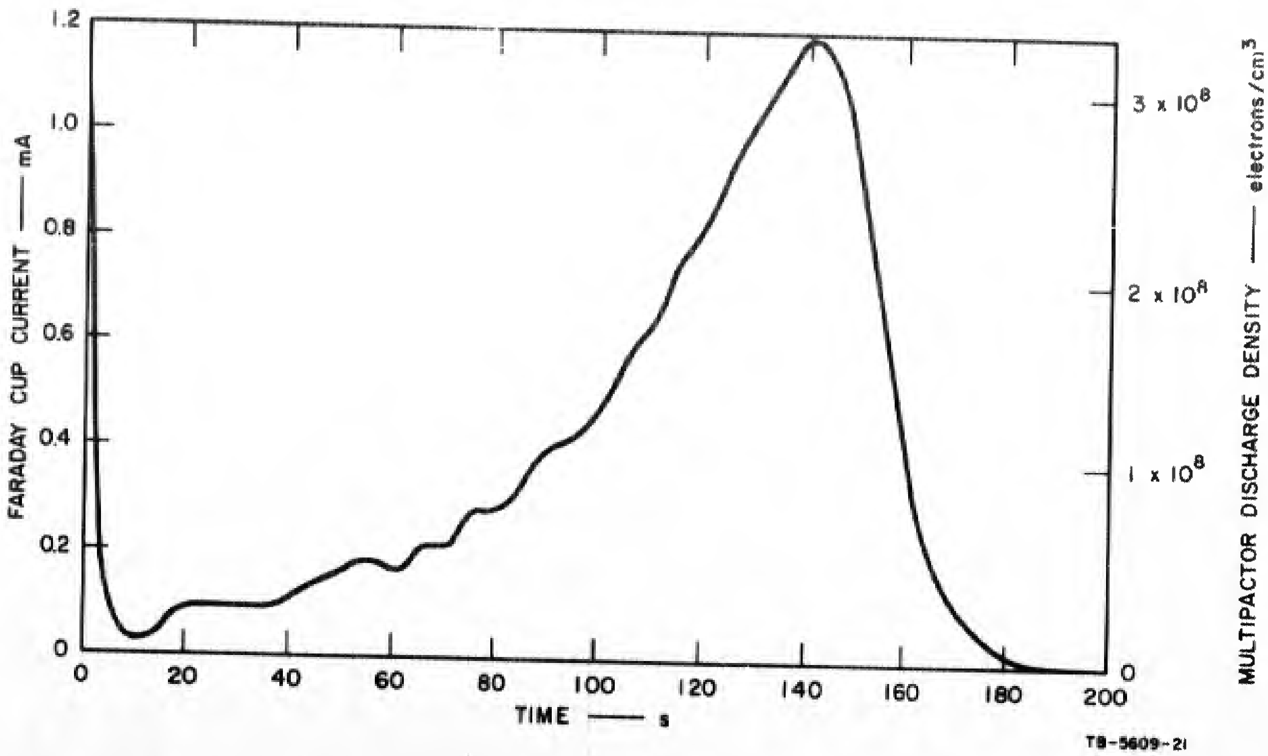

FIG. 10 MULTIPACTOR ELECTRON DENSITY vs. TIME, CASE 2. Strip-line balun, 3/16" spacing, 1800 W power; 2×10^{-5} torr, under vacuum 7-½ hrs; 4 hrs 7 minutes since last test.

stantial electron densities of 1×10^8/cc (1.25 percent of critical) are obtained for longer than 70 seconds. On successive trials of this series, the secondary peak gradually moved out in time, and the magnitudes of the primary and secondary peaks gradually decreased.

D. Conclusions

The laboratory tests show that the GAM discharge (initial phase of a multipactor discharge), can persist for times ranging from a few seconds up to a few minutes. Substantial electron densities can simultaneously exist, and appreciable heating can occur. The effect of a GAM discharge on an antenna is an erratic variation in VSWR. The GAM effects are apparently associated with surface gas desorption and interior outgassing, as evidenced by the optical emission during this phase. By virtue of this association with outgassing and the subsequent increase in local gas pressure, the GAM discharge exhibits some aspects of a gas discharge.

While the GAM discharge is transitory in nature, it may persist long enough on high-Q antennas to be a problem on rocket flights, where the entire peak portion of flight may be only a minute in duration, or on reentry flights, where a minute's flight time at 20 kft/sec may involve an appreciable range.

IV FLIGHT-TEST RESULTS

A. Introduction

The flight-test results relating to anomalous breakdown of the VHF quadraloop antennaare discussed in this section. These results are compared to laboratory data obtained for the gas-augmented-multipactor discharge described in Sec. III. It is concluded that the anomalous breakdown was a gas-augmented-multipactor discharge, and that some classical multipacting occurred at high altitude. Evidence is offered to support these conclusions.

B. General Discussion

The anomalous breakdown occurred at high altitudes, above the normal altitude for gas-discharge breakdown predicted from laboratory experiments. The breakdown was evidenced by sudden changes in the incident and reflected power. These changes appeared as distortion of the trapezoidal power-modulated cycles.

The following discussion relates primarily to the ascent portion of the rocket flight. Similar effects are evident on the descent portion. Some flight-test results have previously been reported.[1,6] Sukys has described the antenna breakdown power, and antenna VSWR, during the flight.[6] Table III lists the antenna breakdown conditions during ascent, according to the original interpretation of the flight test record (i.e., trapezoidal modulation indicates absence of breakdown), and according to the new interpretation inferred from the gas-augmented-multipacting discharge (GAM) experiments and a further review of the flight-test record.

The flight-tests results that support the new interpretation given here are the result of analyses of the incident and reflected power data on the quadraloop antenna in the light of the laboratory simulations. The significant indicators are the magnitude and duration of VSWR changes as a function of power level and altitude.

Table III

QUADRALOOP ANTENNA BREAKDOWN DATA, FLIGHT AD 6.841

Flight Time Interval (sec)	Flight Altitude Range (kft)	Breakdown Conditions	
		Original Interpretation	New Interpretation
0- 23	0- 61	None	None
24- 71	65-229	Gas Breakdown	Gas Breakdown
72- 75	230-239	None	None
76- 97	239-286	First Anomalous Period	GAM
98-107	286-304	None	Multipactor
108-116	305-315	Second Anomalous Period	GAM
117-150	316-341	None	None, or slight multipactor
	Descent		
150-197	341-296	None	None, or slight multipactor

C. Results

1. Telemetry Incident and Reflected Power Records

Figure 11 shows some non-breakdown and gas-discharge-breakdown modulated-power records observed during the flight test. The trapezoidal modulation is quite apparent. The rapid changes in incident and reflected power are indicative of gas-discharge breakdown. The antenna VSWR prior to breakdown, or during breakdown, and the breakdown initiate and extinguish powers, can be readily determined from such a record. Once the incident and reflected power level traces have been analyzed, certain characteristic modulation waveforms appear that serve as indications of the type of breakdown taking place. Figure 11 is a typical example. In general, the gas-discharge breakdown results in severe modification of the incident as well as the reflected power level. The effect on the incident power is a characteristic of the RF power system. Multipacting breakdown, in its various forms, usually results in lower VSWR levels, and their effects are observed predominantly in reflected power level changes.

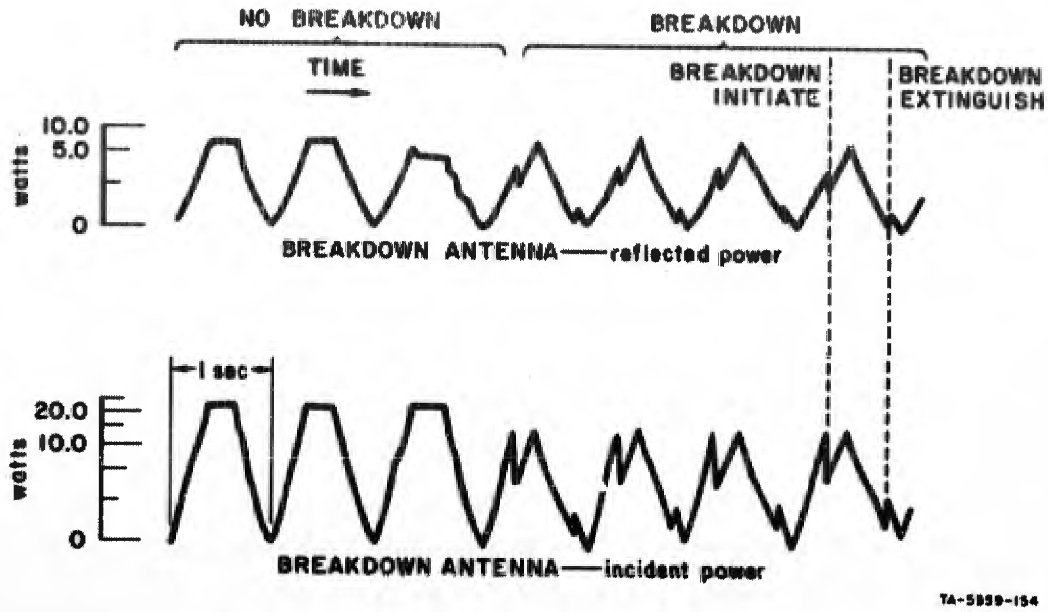

FIG. 11 TELEMETRY RECORD OF VHF ANTENNA GAS-DISCHARGE BREAKDOWN

The behavior of the VSWR as the power is varied produces modulation-cycle shapes during the intervals of anomalous breakdown, that differ in many respects from those of the gas discharge phase. Figure 12 shows typical incident and reflected power records at two different times during the first anomalous breakdown interval. The records are significant in that they show saturation (flat tops), which is not a characteristic feature of gas-discharge breakdown. That is, during the period of anomalous breakdown, notches characteristic of gas-discharge-breakdown onset occurred only after some delay in reaching the maximum power level. In both the first anomalous and second anomalous intervals, the modulation cycles gradually trend toward the trapezoidal shapes presumably characteristic of non-breakdown. Unlike the gas discharge, another feature of the anomalous breakdown is the irregularity from cycle to cycle.

In general, the features that distinguish anomalous breakdown observed during the Nike-Cajun flight from gas-discharge breakdown, are also observed in the GAM discharge in the laboratory. Figure 12 should be contrasted with Fig. 7, representative of a GAM discharge.

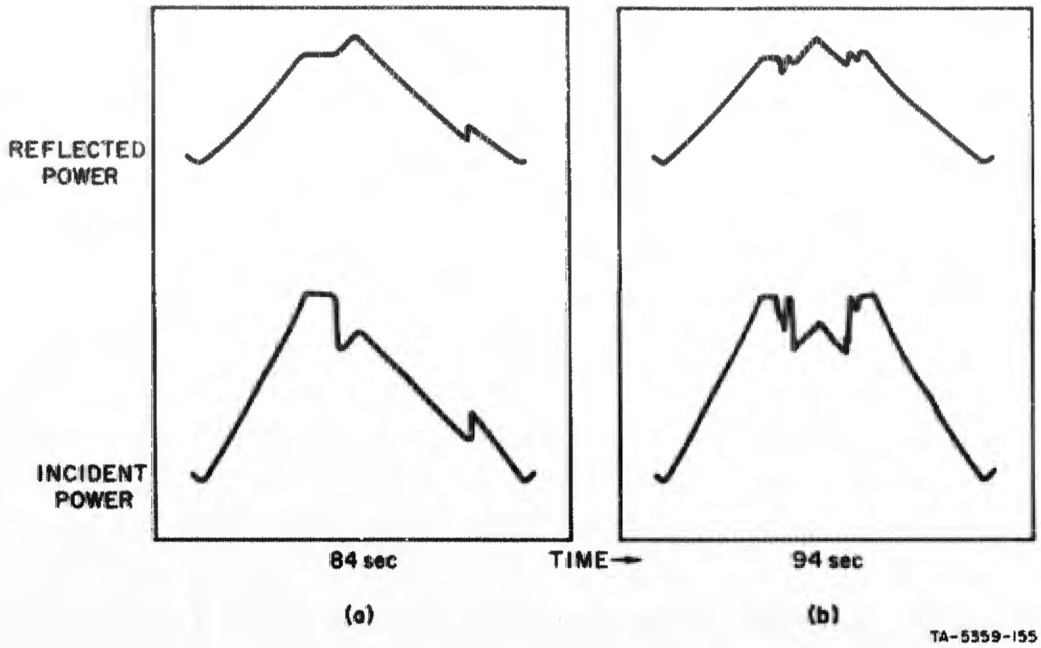

FIG. 12 TELEMETRY RECORD OF VHF ANTENNA ANOMALOUS BREAKDOWN
(a) 84 sec
(b) 94 sec

2. Antenna VSWR

a. Pre-Breakdown VSWR

Sukys has given a graph of VSWR for the quadraloop antenna throughout the course of the rocket flight.[6] His curve of VSWR immediately prior to breakdown is reproduced here as Fig. 13(a). When breakdown occurred, the VSWR values were inferred from the power levels immediately preceding the notches, indicating the change in VSWR caused by the breakdown. When only trapezoidal shapes appeared, the VSWR values were determined from the peak values of incident and reflected power.

The data of Fig. 13(a) are peculiar, because there are some abrupt changes in VSWR as well as some gradual changes. The changes during launch and splashdown are believed to be due to aerodynamic stresses. The abrupt changes have not been explained at all. The remaining gradual change in VSWR at 220-260 kft (ascent) is explainable by assuming that a GAM discharge and multipacting occurred. In

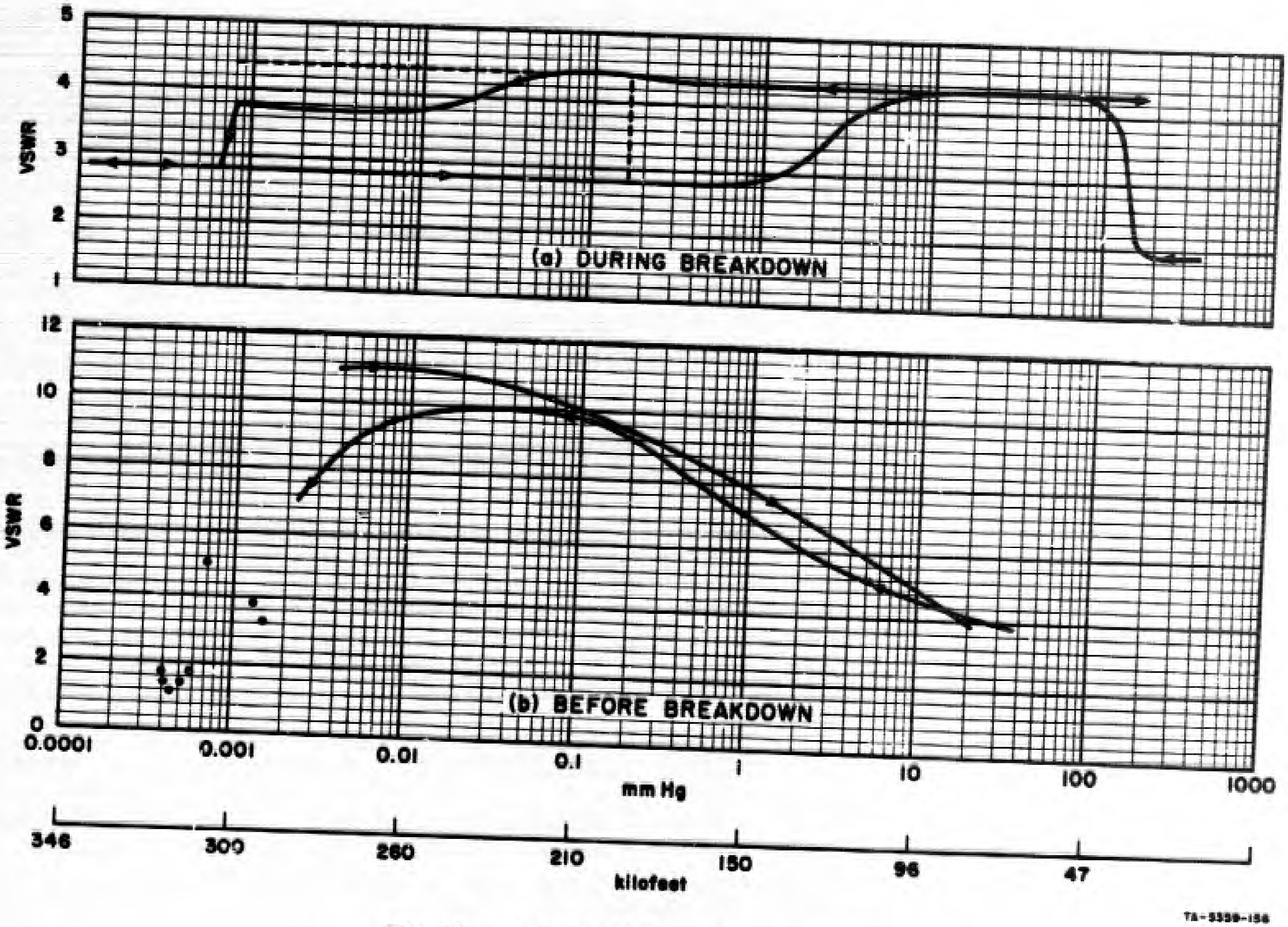

FIG. 13 VSWR OF VHF ANTENNA — FLIGHT TEST
(a) Before Breakdown
(b) During Breakdown

that case, it is believed that there is no change in VSWR--the apparent change shown in Fig. 13(a) is believed to be due to inclusion of multipacting breakdown data in what is otherwise pre-breakdown data.

The laboratory experimental results found that gas-enhanced multipacting (the final GAM discharge phase) and multipactor breakdown (classical multipacting) often lowered the reflected power by improving the match. This occurred without seriously changing the general shape of the modulation cycles and often without producing sudden notches in the modulation shapes. The multipactor breakdown thus effectively clipped the tops of the reflected power traces, by improving the match when breakdown started. The clipping refers to the fact that the reflected power pulse appears to saturate at a level below the no-breakdown case, and prior to the time the incident power reaches a constant value. Accordingly, the flight-test data was reexamined to determine whether such clipping due to match improvement had occurred.

Traces of reflected and incident-power-modulation cycles at 20 sec (48 kft), prior to any breakdown, were prepared. These traces were overlaid on suspect trapezoidal data. Any clipping was immediately apparent because of the increased length of the saturation level. Changes in VSWR were also apparent as slope changes on the slanted sides of the reflected power trapezoidal modulation.

All flight-test data from Cycle 72 (after last gas-discharge breakdown) through Cycle 197 (start of continuous breakdown on descent) were examined. Clipping definitely occurred for Cycles 84 (during the first anomalous period) through 107 (just prior to the second anomalous period). It was also found that the VSWR prior to clipping was exactly the same as the non-breakdown VSWR.

On Cycle 108, the VSWR changed abruptly, and the second period of anomalous breakdown began. The shapes of the modulation cycles indicate that clipping still occurred during the second anomalous breakdown period. Figure 14, Cycle 115 (315 kft), is an example of clipping.

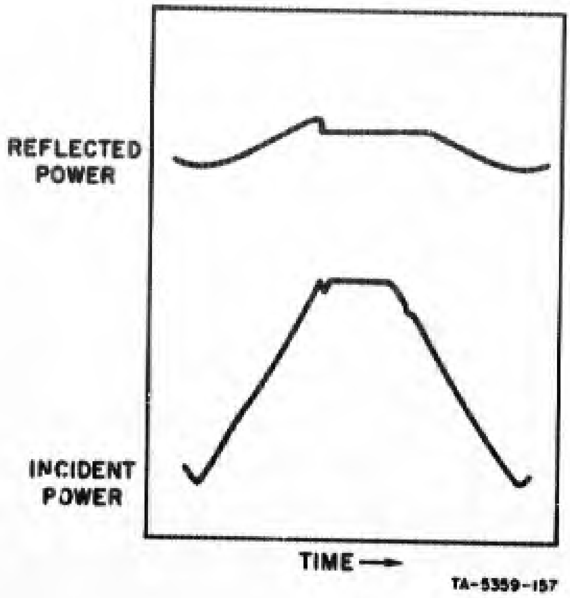

FIG. 14 CLIPPING OF REFLECTED POWER MODULATION, CYCLE 115

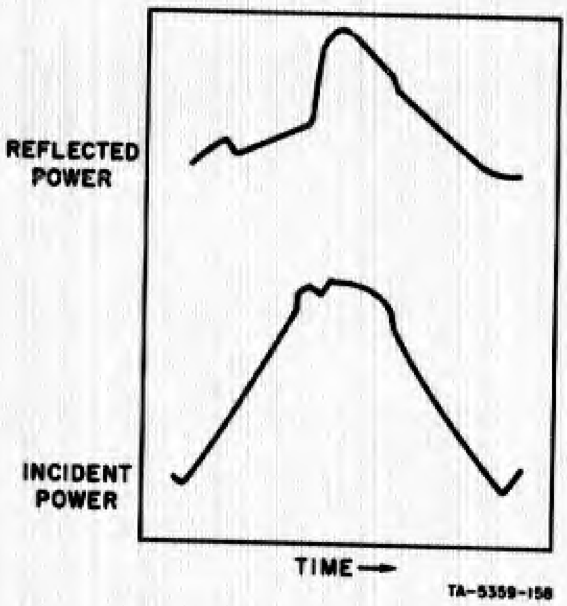

FIG. 15 SUDDEN VSWR CHANGE AND START OF SECOND PERIOD OF ANOMALOUS BREAKDOWN, CYCLE 108

It is concluded that in the initial analysis[6] some multipacting breakdown or gas-enhanced multipacting breakdown results were inadvertently included with otherwise non-breakdown VSWR results. The results have therefore been modified as indicated by the dashed curve in Fig. 13(a). The pre-breakdown VSWR is constant, except for the two unexplained abrupt shifts, and excluding the launch and splash-down phases.

The overlay technique was one indicator of clipping. Another indicator was also used on the trapezoidal reflected-power-modulation cycles of the flight test. This was the ratio of top length to base length for the trapezoid. This indicator eliminated any errors due to changing cycle duration. In actuality, the base length varied by less than 1.6 percent. Table IV lists the indicator at various flight stages. The indicator has been normalized to the prelaunch value.

Table IV

CLIPPING INDICATOR, FLIGHT AD 6.84

Time (sec)	Flight State	Indicator Ratio	Occurrence of Multipacting
-1	Prelaunch	1.00	No
23	Before gas breakdown	1.03	No
73	Between gas breakdown and 1st anomalous period	1.13	No, or slightly
98	Between 1st and 2nd	1.40	Yes
107	anomalous breakdown periods	1.33	Yes
118	After 2nd anomalous period	1.19	Perhaps
155	Peak altitude	1.26	Perhaps
197	Last descent cycle before breakdown	1.26	Perhaps

The clipping indicator thus offers some evidence of classical multipacting occurring at high altitudes.

b. Breakdown VSWR

Figure 13(b) shows the VSWR during breakdown (peak values), given in Ref. 6. The data include only instances of breakdown that produce notches in the trapezoidal modulation shapes of the power records.

In the altitude range of interest, above 229 kft, after the last gas discharge has occurred, the relative magnitudes and behavior of the flight breakdown VSWR are remarkably similar to those observed in the laboratory for the same antenna undergoing a GAM discharge. Thus, the breakdown VSWR is appreciably less than that at the last cycle of gas discharge, and gradually decreases toward the prebreakdown value. In several cases between 229 kft and 305 kft (where a sudden VSWR shift occurred), the VSWR during breakdown is actually below that of no breakdown. This was a familiar occurrence during the laboratory GAM discharge experiments.

Because the effect of breakdown on the antenna VSWR varies with the initial VSWR level, more quantitative analysis is not worthwhile, due to the vastly different pre-breakdown VSWR of the flight-test antenna and the laboratory test antenna.

3. Anomalous Breakdown Duration

The first anomalous breakdown period persisted from 76 sec to 97 sec in the flight, for a total of 22 sec. The second anomalous breakdown period persisted from 108 sec to 116 sec during the flight, for a total of 9 sec. The total period of anomalous breakdown was 31 sec. Reference to Table II, the laboratory data for duration of quasi-gas-discharge phase and overall GAM discharge phase, establishes that the duration of anomalous breakdown observed during flight is in good agreement with the duration of the quasi-gas discharge in the laboratory experiment.

It is expected that the poor initial match of the flight-test antenna would result in relative insensitivity of the antenna to quasi-gas discharges or GAM discharges, and very poor sensitivity to multipacting discharges. This expectation, in conjunction with the observed

duration of the anomalous discharge, suggests that the anomalous breakdown corresponded to the quasi-gas-discharge phase of a gas-augmented multipactor discharge.

4. Effect of Power Increase

Figure 15 shows the modulation cycle shapes recorded during Cycle 108 after launch. On this cycle, the antenna VSWR changed abruptly, as described in Ref. 1. This cycle also marked the onset of the second anomalous breakdown period. The power delivered to the antenna increased from 14.4 W (peak of Cycle 107) to 23 W (peak of Cycle 109).[1] This 2-dB increase in antenna power is believed to have triggered the second period of anomalous breakdown.

Similar effects have been observed at Stanford Research Institute, where an increase in RF power on an existing multipactor discharge increases the visible luminosity of the discharge, and also increases the electron density of the discharge. This increase in intensity or luminosity generally only persists for a short time (~ 10 sec), if the discharge has run for some time prior to the power increase.

The power increase is believed to increase the electron density of the multipactor discharge. The increased electron density in turn increases the gas released from the multipacting surfaces, either directly by bombardment of adsorbed surface gas or indirectly by heating the surface. The increased gas density leads to increased positive ion production by collision with the multipacting electrons. The changed ion production thereupon allows an increase in the steady-state electron density of the discharge, whereupon the cycle begins again, and continues until sufficient surface gas has been released so that the gas evolution rate decreases.

The gas released during this hypothetical process would interact with the RF field of an antenna to produce a GAM discharge. The quasi-gas discharge phase of the GAM discharge would explain the second anomalous period of breakdown, associated withthe 2-dB power increase.

D. Conclusions

The flight-test data for the VHF quadraloop antenna have been re-examined and show various high-altitude peculiarities other than the anomalous breakdown. These peculiarities are: gradual pre-breakdown VSWR variation, breakdown VSWR decrease during ascent, reflected power clipping, and repeated anomalous breakdown following a power increase. The anomalous breakdown has characteristics atypical of gas-discharge breakdown. These are: delayed breakdown, irregular variation from cycle to cycle, and a trend toward increased clipping with time.

The above data can be satisfactorily exaplained as resulting from a gas-augmented-multipactor discharge. The anomalous breakdown corresponds to the quasi-gas discharge phase of a GAM discharge, while the VSWR peculiarities, delayed breakdown, and pulse clipping correspond to either the transition cycles or the gas-enhanced-multipacting-breakdown phase of a GAM discharge.

BLANK PAGE

V CONCLUSIONS

A. Anomalous Breakdown

The anomalous high-altitude voltage breakdown observed on the VHF quadraloop antenna aboard Nike-Cajun flight AD 6.841 was due to a gas-augmented-multipactor discharge. In addition to the anomalous breakdown, a high-altitude multipactor discharge of the usual kind occurred over at least one portion of the ascent (286-304 kft), and may have occurred over other portions of the ascent and descent as well.

The above conclusions result from comparison of internal evidence and peculiarities of the flight-test record with observations of laboratory multipacting under simulated flight conditions, and some additional laboratory observations on multipacting.

B. Gas-Augmented-Multipactor Discharge

A GAM discharge is the initial or transient phase of a multipactor discharge, in which a dynamic pressure change is occurring. The pressure change may be externally produced, or may result from outgassing of electrodes, or liberation of adsorbed surface gases and/or contaminants. A GAM discharge produces effects that resemble some aspects of a gas-discharge breakdown. During a GAM discharge, substantial electron densities can occur, and appreciable heating may follow as a result. The GAM discharge can noticeably affect the VSWR of an antenna.

A GAM discharge can be expected to occur on rocket-borne antennas radiating a sufficiently high power. Such a discharge may affect antenna performance. The severity of the problem is difficult to predict; however, it depends upon surface conditions, the antenna Q, and geometry as well as the radiated power level. It has been found that RF arcs sometimes occurred at high power, following an initial multipactor discharge (Ref. 2, pp. 18-22). Such arcs cause severe physical damage, and might destroy or disable a high-power antenna should they occur.

The GAM discharge will only occur when the multipacting breakdown power-level threshold is exceeded. For most antennas, the multipactor breakdown threshold exceeds the gas-discharge power level threshold. In those cases, the gas-discharge threshold also bounds the GAM discharge threshold. However, it is possible for the multipactor breakdown threshold to be lower than the gas-discharge breakdown threshold for certain combinations of frequency, antenna size and configuration, and surface materials. In these latter cases, a GAM discharge may occur at high altitudes without a gas discharge occurring at all, at lower altitudes.

REFERENCE

1. J. E. Nanevicz, J. B. Chown, E. F. Vance, and J. A. Martin, "SRI Participation in Voltage Breakdown and Rocket Charging Experiments on Nike-Cajun Rocket AFCRL AD 6.841," Scientific Report 3, Contract AF 19(628)-4800, SRI Project 5359, Stanford Research Institute, Menlo Park, California (August 1966).

2. G. August and J. B. Chown, "Power-Handling Capability of Radiating Systems in the Exoatmosphere," Tech. Report 2, Subcontract No. 324 under Contract AF 19(628)-5167, SRI Project 5609, Stanford Research Institute, Menlo Park, California (September 1967).

3. P. L. Copeland, "Secondary Electrons from Contaminated Surfaces," Phys. Rev., Vol. 35, No. 8, pp. 982-988 (15 April 1930).

4. R. Kollath, "Sekundaerelektronen-Emission fester Koerper bei Bestrahlung mit Elektronen," pp. 259, 266, 267, 274 in Encyclopedia of Physics, Vol. 21, S. Fluegge, editor (Springer-Verlag, Berlin, 1956).

5. S. Dushman, Vacuum Technique, pp. 44-65, 313-332 (John Wiley and Sons, Inc., New York, N.Y., 1955).

6. R. Sukys, "Flight Determination of Voltage Breakdown Characteristics of Missile Antennas," Final Report, Contract AF 19(628)-479, Electronics Research Laboratory, Northeastern University, Boston, Massachusetts (31 May 1966).